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PROCEEDINGS

EVALUATION OF ENVIRONMENTALLY ACCEPTABLE MULTI-LAYER COATING SYSTEMS AS DIRECT SUBSTITUTES FOR CADMIUM PLATING ON THREADED FASTENERS

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ABSTRACT

Cadmium has been identified by the United States Army's Tank and Automotive Command as a threat to worker health and the environment. Based on already completed cadmium substitute testing, an evaluation program was conducted to quantify the performance of environmentally acceptable, multi-layer coatings that could be directly substituted for cadmium on threaded fasteners. The performance issues investigated included coating system lubricity and corrosion control performance. Data were generated from both natural marine atmosphere exposure tests and laboratory evaluations. Test specimens were prepared by applying sacrificial plating layers and lubricous topcoat materials to commercially available 1/2-20 UNC Fine, Grade 5 fasteners. Experimental analyses included realistic torque-tension curve development, marine atmosphere exposure testing, and ASTM B 117 salt fog evaluations. Program findings indicate that ASTM B 633 zinc coatings (without the Type II or III chromate passivation treatment) exhibited torque tension behavior that was directly comparable to that of the cadmium experimental controls. Corrosion control performance test results indicated that regardless of underlying plating chemistry, systems topcoated with Everlube 6108 performed as well as the cadmium experimental controls.

INTRODUCTION

The Army Materiel Command's, Acquisition Pollution Prevention Support Office (AAPPSO) identified cadmium plating as an environmentally unacceptable process in 1989. Cadmium is considered unacceptable because it adversely impacts the environment and poses a threat to worker health. Cadmium is considered such a threat to workers that the Occupational Safety and Health Administration (OSHA) recently revised their cadmium regulations. OSHA, in its September 14, 1992 "Occupational Exposure to Cadmium; Final Rules," reduced the allowable airborne concentration of cadmium in the work-place by 95% (from the previously accepted Permissible Exposure Limit or PEL). Compliance with the OSHA Cadmium Standard is expected to cost domestic industries $159 million/year.(1)

The environmental unacceptability of cadmium has prompted many other countries to develop regulations or "bans" on the material. For example, Sweden enacted a comprehensive cadmium ban in 1985.(2) Finland also restricted cadmium usage in 1992 and Germany has prohibitions against the use of some cadmium compounds.(3)

Given the environmental and worker health problems associated with continued cadmium use, many Army activities are trying to eliminate their applications for the metal. The AAPPSO has been researching cadmium alternatives since 1989 and completed a major environmentally acceptable alternative screening program in 1991.(4) Based on the AAPPSO sponsored cadmium alternative screening program results, and private sector data, representatives of the Army's Tank and Automotive Command (TACOM) decided to research "direct" cadmium substitutes.(5)

The "direct" cadmium substitute concept evolved when TACOM staff reviewed the available technical literature and concluded that no universal, "one-for-one" cadmium substitute was likely to be developed in the near future. However, TACOM staff felt that by combining sacrificial plating layers and lubricous topcoats, a coating system that would mimic the performance of cadmium plating (both torque-tension and corrosion control) closely enough to allow direct substitution on Army tactical vehicles could be developed. The development of this "direct" substitute coating would allow TACOM to avoid the high costs associated with rewriting all the Army vehicle maintenance manual fastener torque requirements that were originally developed using cadmium coated fasteners.

TACOM staff commissioned Ocean City Research Corporation to conduct a realistic test program with the overall objective of identifying a "direct" cadmium

substitute that would mimic the torque-tension relationship exhibited by QQ-P-416E, Class 3, Type II cadmium coatings on Grade 5 carbon steel fasteners and still exhibit comparable (or better) substrate corrosion control performance.

TECHNICAL APPROACH

TEST MATRIX - Table I presents the multi-layer cadmium substitute program test matrix and target coating thickness summary. The matrix lists the sacrificial plating layers and the six alternative lubricous topcoat materials. The test matrix shows the coating systems roughly divided into three base plating layer groups. For clarity, these three data set groupings will be used throughout this discussion.

The plating layers described in the Table I test matrix were applied in accordance with the following Federal or consensus specifications.

Cadmium	-	Federal Specification QQ-P-416E, Class 3, Type II
Zinc	-	ASTM B 633, Type I
Zinc/Nickel	-	Draft ASTM specification
Zinc/Cobalt	-	Commercial specification

Because chromic acid based passivation treatments are considered environmentally unacceptable, none of the test cadmium alternatives were passivated with these solutions. However, because many Army tactical vehicle maintenance manuals were developed using chromated cadmium fastener performance data, the cadmium coated experimental controls did receive a Type II chromate treatment. Excluding these experimental controls, the alternative plating layers are considered environmentally acceptable because they do not contain lead, chromium, or cadmium, and are not plated from a cyanide bath.

The lubricous topcoats shown in Table I were applied by commercial vendors using their "best practices." The Xylan 5420, Everlube 6108 and Everlube 9000 coatings were applied from low VOC solutions and contain PTFE (Teflon). The SACI 445A coating was applied from an aqueous bath and contains calcium carbonates and sulfonates. The Alumzite 132 coating consists of aluminum particles in an organic binder Finally, the Molykote M3400A (a MIL-L-46010A molybdenum disulfide dry film lubricant) was included in the program even though the as applied material contains more than 5 lbs/gallon VOCs. Because these MIL-L-46010A lubricants are widely used by the Army, this material was included in the test matrix as an experimental control. None of the lubricous topcoats contained lead or soluble chromates.

TEST SPECIMENS - Figure 1 shows a representative cadmium coated test fastener set. Each test fastener set included a 3-inch long, 1/2-20-UNC Fine, Grade 5 threaded bolt, a mating nut, and two 1/2-inch washers. The fasteners were procured from commercial suppliers and were not undersized to accommodate subsequent coatings. Plating vendors were required to coat entire specimen lots using the same military or commercial specifications. Topcoat vendors were also instructed to coat the plated fastener lots using the same "best practices" on each item.

COATING THICKNESS QUALIFICATION - An Elcometer 300 film thickness gauge was used to measure non-magnetic coating thicknesses. Because the Zn/Ni and Zn/Co coatings might have exhibited magnetic properties, their thicknesses were initially measured using representative metallography. Metallographic thicknesses were found to correlate well with Elcometer 300 readings and this device was used for all subsequent measurements. After the plating and topcoating processes, layer thicknesses were measured at replicate sites on individual nuts, washers, bolt heads, and bolt shanks. After coating, ten representative fastener sets were selected from each plating/topcoat system group. The thickness data from these representative fasteners were then collected and analyzed.

TORQUE-TENSION TESTING - Figure 2 shows the program torque-tension measurement apparatus. The apparatus is an evolutionary design based on devices described in published literature and in the SAE Recommended Practice J174, "Torque-Tension Test Procedure."(6,7) The apparatus shown in Figure 2 consists largely of conventional automotive mechanic's tools. These conventional tools were combined with extremely accurate compression and torque sensors to allow both realistic and accurate data collection. The Omega DP-41-S strain gauge and DP-80 digital strain indicators were calibrated by the vendors (+ or - 0.25%) and programmed to directly convert the torque and strain sensor inputs into foot*lbs and kips units for direct, real-time scaling on an X-Y recorder. The use of actual mechanic's tools, similar to those available in Army tactical vehicle maintenance shops, allowed fastener head slippage, galling, and misfits to realistically contribute to the data collection process.

The bolt head shown in Figure 2, Detail A was placed in a fixed socket and the instrumented torque wrench was mounted on the nut. To minimize program variables and address specific Army needs, only unlubricated (no oil or grease) fasteners were tested. As shown in Detail A, a series of machined stainless steel spacing washers and a leveling device were mounted on either side of instrumented compression load cell (calibrated to measure compression loads up to 100 kips or 444,820 Newtons [N]). The leveling device consisted of a nested hardened steel convex disk and concave

plate. The nesting components have large holes in their centers through which the test fastener passed. Any eccentricity in the applied load across the leveling device was absorbed by motion between the two (convex/concave) mating surfaces. As torque was manually applied to this assembly, the instrumented wrench sensor and compression cell directly generated a data plot on an
X-Y recorder.

EXPOSURE TESTING - Test fasteners were exposed at the Ocean City Research Corporation, Sea Isle, NJ marine exposure test site. The fasteners were exposed using two differ~~~ test specimen support assemblies to facilitate subsequent analyses. Both marine site fastener test assemblies were subject to daily seawater spray.

Figure 3 shows two of the marine atmosphere exposure test rigs. The fasteners shown in the upper portion of the picture were threaded onto non-conductive phenolic/glass composite plate/tube assemblies with the nut/bolt interface exposed to the marine environment at an angle of 45 degrees facing south. The orientation of these specimens maximized the corrosive conditions at the nut/bolt interface. These specimens were torqued uniformly to create an estimated 10 kips [44,482 N] tensile load on each fastener. The breaking torques required to disassemble groups of selected test fasteners were measured after 2500, 5000, and 7000 hours of marine atmosphere exposure testing. During testing, all specimens were inspected for visible corrosion in accordance with a modified ASTM D 610 rating scale. The ASTM D 610 standard was modified to compensate for the difficulties associated with accurately measuring corroded areas on complex fastener surfaces.

The horizontally mounted fasteners with the exposed shanks shown in Figure 3 were intended to create conditions favorable for shank/thread corrosion and stress corrosion cracking. These loaded fasteners were initially torqued to create a fastener tensile load of 10 kips [44,482 N]. During testing, these fasteners will be further tensioned at regular intervals to absorb any system compliance or support frame deformation. These specimen sets were also inspected for visible corrosion in accordance with the modified ASTM D 610 rating scale.

SALT FOG TESTS - Salt fog tests were performed in accordance with ASTM B 117. Three replicate test specimens, from each test coating system group, were assembled and mounted on insulated racks. The assembled fastener specimens were exposed to the salt fog atmosphere for 1000 hours. During testing, all specimens were inspected for visible corrosion in accordance with the modified ASTM D 610 rating scale. These salt fog tests are intended to generate results that may be compared with the Army's historical salt fog test data-base. TACOM staff

acknowledge that salt fog tests have limited usefulness in evaluating corrosion. However, they feel such results could be compared with existing historical data.

RESULTS AND DISCUSSION

COATING APPLICATION ACCURACY - Table II summarizes the average coating thicknesses on the test fastener sets. As shown, the average actual test coating thicknesses varied both above and below the specified target thicknesses. Of the twenty-one test systems (including the cadmium experimental controls), four had average thicknesses lower than those specified. The remaining seventeen systems were thicker than specified and in four cases thicknesses were more than three times (300%) greater than those specified.

The standard deviation data shows that in addition to the overall average thicknesses being inaccurate, many systems varied around those averages by almost as much as the original target system thickness. For example, the actual cadmium thickness standard deviation is 0.19 mils which is almost as large as the specified target thickness of 0.2 mils. Nine of the test systems actually had standard deviations that were greater than the specified coating thickness. These data, when combined with previously reported findings, suggest that specified plating thicknesses on commodity grade fasteners are poorly controlled.(4) Thus, provided cadmium alternative system performance is acceptable, thickness variations assembly should not disqualify environmentally acceptable alternative coatings.

TORQUE TENSION RELATIONSHIPS - Torque-tension curves were generated using replicate as-received fasteners. Initially, fifteen to twenty fasteners from representative coating lots were evaluated using the Figure 2 apparatus. The resulting raw data from these tests were a series of X-Y recorder plots. To facilitate analysis torque intervals of 20 ft*lbs [27 N*m] were arbitrarily selected and corresponding data points on the X-Y plots were identified. Tension values corresponding to these torques were then interpreted from each of the individual raw data plots and loaded onto a computer spreadsheet. These interpreted data are presented in the following figures.

An initial analysis was conducted to determine if coating system torque-tension data distribution were "normal" or "Gaussian." Figure 4 shows the tension data distribution for twenty replicate cadmium coated fasteners at an applied torque of 80 ft*lbs [108 N*m]. As shown, the distribution is nearly normal and as such descriptive statistical analyses would be applicable. Figure 4 and all figures in this paper were initially generated using english measurement units. For clarity, these units are

retained in the figures. SI unit conversions are provided in square brackets below the plot labels and on the actual plot axes.

Figure 5 shows a tension data distribution histogram generated using fifteen replicate zinc-Molykote M3400A coated fasteners. An applied torque of 100 ft*lbs [135 N*m] was selected as the basis for comparison. Again, the distribution appears nearly normal and justifies the application of descriptive statistics. All tested fastener groups exhibited similar "normal" data distributions.

Figure 6 shows the complete torque-tension data from the twenty replicate cadmium coated fasteners used to generate Figure 4. Figure 6 includes the average, minimum, maximum, and standard deviation data. The most important feature of this plot is the significant data scatter. The tension data range at an applied torque of 80 ft*lbs [108 N*m] varies between 7,510 kips [33,406 N] and 10,580 kips [47,062 N]. This range is approximately 36% of the average target tension. The standard deviation at this torque value is also quite large at 720 kips [972 N]. Understanding that these data were generated from the cadmium experimental control, this wide scatter suggests that alternative coatings may also exhibit considerable torque-tension data scatter and still be considered acceptable cadmium substitutes. For the purposes of this discussion, a substitute will be considered acceptable if its torque-tension curve lies within + or - one standard deviation of the cadmium results.

Figure 6 also shows that cadmium coatings exhibit relatively consistent behavior over the entire measured torque-tension range. Cadmium coated fastener tension increased at a slightly decreasing rate as a function of increasing applied torque. To be considered acceptable, any potential cadmium alternative coating would have to exhibit similar, consistent behavior.

The Figure 4, 5, and 6 results were generated by evaluating many replicate fasteners. To improve program efficiency, average and standard deviations from smaller sample sizes were compared to those generated from fifteen or twenty replicates. The objective of this analysis was to identify the minimum number of specimens required to produce representative data. Figure 7 shows representative torque-tension curves generated using five, ten, and fifteen replicate fasteners coated with the Zn-M3400A system. Using the previously stated + or - one standard deviation criteria, Figure 7 shows that results generated from five replicate test fasteners would be as representative of the overall population as those generated from ten or fifteen specimens.

Figure 8 shows the torque-tension data generated from five replicate test specimens with the zinc plating layer substrate and the six alternative topcoats. The cadmium experimental control data has been included on the plot as a reference. With the exception of the Zn-Xylan system, all of the alternative's torque-tension curves have slopes greater than that exhibited by the cadmium experimental control. These greater slopes signify that the alternative coating systems are appreciably more lubricous than cadmium. Because many Army tactical vehicle maintenance manuals specify application torque values, the use of an appreciably more lubricous coating as a "direct" cadmium substitute would result in higher than anticipated clamping forces and possibly cause fastener tensile overload failures. Thus, none of the lubricous topcoat based systems exhibiting slopes greater than cadmium would be considered acceptable substitutes.

However, Figure 8 also shows that the non-topcoated zinc and the Zn-Xylan systems were quite similar to cadmium in overall torque-tension performance. The zinc curve falls almost exactly over the cadmium plot and easily satisfies the one standard deviation criteria as an acceptable cadmium substitute. These data suggest, from a torque-tension standpoint, that zinc plating would be an effective cadmium substitute.

The performance similarities between the Zn-Xylan system and cadmium are surprising. Xylan is a PTFE based coating that is supposedly lubricous. However, the Figure 8 data show the material was actually less lubricous than the uncoated plating layer. Although the Zn-Xylan data falls slightly outside the one standard deviation range, it is interesting that the Zn-Xylan system actually produced torque-tension relationships quite similar to those exhibited by the cadmium controls.

Figure 9 shows the torque-tension data generated from five replicate test specimens with the Zn/Ni plating layer substrate and the six alternative topcoats. The trends discussed during the Figure 8 analysis apply to the Figure 9 data although to a lesser degree. The Figure 9 results show both the un-topcoated Zn/Ni and the Zn/Ni-Xylan systems were slightly less lubricous than cadmium. However unlike Figure 8, the Zn/Ni-Everlube 6108 system was only slightly more lubricous than cadmium and falls just outside the cadmium data one standard deviation range. Thus, although the performance of the Zn/Ni-Everlube system is similar to that of cadmium it would not be considered a direct cadmium substitute.

Figure 10 shows the torque-tension data generated from five replicate test specimens with the Zn/Co plating layer substrate and the six alternative topcoats. The trends discussed during the Figure 9 analysis apply to the Figure 10 results. Again,

both the un-topcoated Zn/Co and the Zn/Co-Xylan systems were slightly less lubricous than cadmium. However unlike Figure 9, the Zn/Co-SACI 445A system, not the Everlube 6108, was only slightly more lubricous than cadmium and is just outside the range to be considered a potential cadmium substitute.

The torque-tension data presented in Figures 8-10 show zinc coatings would be considered a direct cadmium substitute. The Zn-Xylan, Zn/Ni-Everlube 6108, and Zn/Co-SACI 445A would be considered possible cadmium substitutes even though their torque tension curves fell just outside of the cadmium data one standard deviation range.

BREAKING TORQUE ANALYSIS - Figure 11 shows average (five data sets) torque data for the "best performing" cadmium substitutes identified during the Figure 8-10 discussion. The torque data presented includes the applied clamping torque required to create an estimated 10,000 kips [44,482 N] of fastener tension and the average breaking torque required to loosen fastener assemblies that had been subject to 2500-hours of marine atmosphere exposure. By comparing the average clamping and breaking torques, Figure 11 allows the relative interfacial corrosion control performance of the fastener systems to be assessed (i.e. systems with severely corroded nut/bolt interfaces will typically exhibit significantly increased breaking torque values).

Comparing the Figure 11 average applied clamping and breaking torque data does not conclusively demonstrate that any of the Figure 8-10 "best performing" systems experienced nut/bolt interfacial corrosion. With the exception of the un-topcoated zinc specimens, all of the "best performing" cadmium alternatives exhibited breaking torques that were lower than the clamping torques - an anticipated result considering that no interfacial corrosion was visually detected. The slight increase in the breaking torque relative to the clamping torque for the un-topcoated zinc specimen is not statistically significant, but does suggest that longer term interfacial corrosion tests (to be presented in October 1993) must be carefully reviewed. If the un-topcoated zinc fastener breaking torque values increase with extended marine atmosphere exposure, the acceptability of this system as a cadmium substitute would be questionable.

MARINE ATMOSPHERE/SALT FOG CORROSION CONTROL PERFORMANCE - Figure 12 presents the average, modified ASTM D 610 substrate corrosion control ratings generated by averaging data from three representative, replicate test fasteners. Marine site corrosion control performance data was collected after 2500 hours of atmospheric exposure. Salt fog data was

collected after 1000 hours of ASTM B 117 exposure. An initial review of the Figure 12 data shows that the salt fog test results do not correlate well with the marine atmosphere exposure test results. For example, the marine atmosphere data shows the following four systems exhibited no substrate corrosion after the 2500 hour exposure period; cadmium, Zn-Everlube 6108, Zn/Ni-Everlube 6108, and Zn/Co-Everlube 6108. The salt fog data exhibited a completely different trend. Based on the salt fog data, the systems offering the most effective corrosion control performance were: Zn-Everlube 6108, Zn/Co-Xylan, cadmium, Zn/Ni-Xylan and Zn/Ni-Alumzite. Because the salt fog results do not accurately reflect the corrosion control performance trends apparent at the marine atmosphere exposure site, the remainder of this discussion will focus on the marine atmosphere results.

A comparison of the "best performing" cadmium substitutes identified during the Figure 8-10 discussion with the Figure 12 results shows the un-topcoated zinc systems that mimicked cadmium's torque tension performance so closely, performed relatively poorly in the marine atmosphere corrosion control tests. However, the Zn-Xylan and Zn/Ni-Everlube 6108 systems that appeared to offer roughly comparable torque-tension performance to the cadmium controls also appear roughly comparable in the corrosion control tests. Because the Zn-Xylan and the Zn/Ni-Everlube 66108 systems offered comparable corrosion control performance and exhibited torque-tension performance comparable to cadmium, these two systems might be considered as possible cadmium substitutes.

CONCLUSIONS

The following are the program conclusions to-date:

1. The actual, average applied thicknesses on seventeen systems were thicker than specified and in four cases thicknesses were more than three times (300%) greater than specified. In addition, variations within groups were frequently as large as the original target thickness. These data suggest that only the most significant fastener thickness variations should impact the cadmium alternative selection.

2. Torque-tension analyses indicate that cadmium coatings are not appreciably more lubricous than ASTM B 633, Type I zinc plating layers and that the addition of a lubricous topcoat may actually allow excessive fastener tension for given torque levels. On the basis of torque-tension tests, a simple zinc coating appears to be the most effective cadmium substitute coating.

3. Corrosion control performance data show ASTM B 117 salt fog test results do not accurately reflect marine atmosphere corrosion control performance.

4. Corrosion control performance data show that any plating substrate, when topcoated with Everlube 6108 provided corrosion control performance comparable to that of the cadmium experimental controls.

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TABLE I

Coating System Test Matrix and Specified Thickness

SYSTEM NUMBER	PLATING LAYER	TARGET THICKNESS (µm)(mils)	LUBRICOUS TOPCOAT	TARGET THICKNESS (µm)(mils)	TOTAL SYSTEM TARGET THICKNESS (µm)(mils)
Control	Cadmium	5.1/0.2	None	0.0/0.0	5.1/0.2
1 Control	Zinc	12.7/0.5	None	0.0/0.0	12.7/0.5
2	Zinc	12.7/0.5	Xylan	12.7/0.5	25.4/1.0
3	Zinc	12.7/0.5	E6108	25.4/1.0	38.1/1.5
4	Zinc	12.7/0.5	E9000	12.7/0.5	25.4/1.0
5	Zinc	12.7/0.5	M3400A	12.7/0.5	25.4/1.0
6	Zinc	12.7/0.5	Saci 445A	12.7/0.5	25.4/1.0
7	Zinc	12.7/0.5	Alumzite	12.7/0.5	25.4/1.0
8 Control	Zn/Ni	5.1/0.2	none	0.0/0.0	5.1/0.2
9	Zn/Ni	5.1/0.2	Xylan	12.7/0.5	17.8/0.7
10	Zn/Ni	5.1/0.2	E6108	25.4/1.0	30.5/1.2
11	Zn/Ni	5.1/0.2	E9000	12.7/0.5	17.8/0.7
12	Zn/Ni	5.1/0.2	M3400A	12.7/0.5	17.8/0.7
13	Zn/Ni	5.1/0.2	Saci 445A	12.7/0.5	17.8/0.7
14	Zn/Ni	5.1/0.2	Alumzite	12.7/0.5	17.8/0.7
15 Control	Zn/Co	5.1/0.2	none	0.0/0.0	5.1/0.2
16	Zn/Co	5.1/0.2	Xylan	12.7/0.5	17.8/0.7
17	Zn/Co	5.1/0.2	E6108	25.4/1.0	30.5/1.2
18	Zn/Co	5.1/0.2	E9000	12.7/0.5	17.8/0.7
19	Zn/Co	5.1/0.2	M3400A	12.7/0.5	17.8/0.7
20	Zn/Co	5.1/0.2	Saci 445A	12.7/0.5	17.8/0.7
21	Zn/Co	5.1/0.2	Alumzite	12.7/0.5	17.8/0.7

TABLE II

Coating System Applied Thickness

SYSTEM NUMBER	PLATING LAYER	LUBRICOUS TOPCOAT	TOTAL SYSTEM TARGET THICKNESS (µm)(mils)	AVERAGE ACTUAL SYSTEM THICKNESS (µm)(mils)	ACTUAL SYSTEM STANDARD DEVIATION (µm)(mils)
Control	Cadmium	None	5.1/0.2	8.44/0.33	4.79/0.19
1 Control	Zinc	None	12.7/0.5	9.89/0.39	5.98/0.24
2	Zinc	Xylan	25.4/1.0	36.86/1.45	13.80/0.54
3	Zinc	E6108	38.1/1.5	30.92/1.22	13.78/0.54
4	Zinc	E9000	25.4/1.0	83.66/3.29	45.59/1.79
5	Zinc	M3400A	25.4/1.0	27.77/1.09	15.17/0.60
6	Zinc	Saci 445A	25.4/1.0	60.70/2.39	28.06/1.10
7	Zinc	Alumzite	25.4/1.0	24.88/0.98	11.96/0.47
8 Control	Zn/Ni	none	5.1/0.2	11.57/0.46	5.65/0.22
9	Zn/Ni	Xylan	17.8/0.7	36.87/1.45	11.02/0.43
10	Zn/Ni	E6108	30.5/1.2	18.75/0.74	6.62/0.26
11	Zn/Ni	E9000	17.8/0.7	65.67/2.59	24.50/0.96
12	Zn/Ni	M3400A	17.8/0.7	28.36/1.12	20.49/0.81
13	Zn/Ni	Saci 445A	17.8/0.7	61.60/2.43	29.72/1.17
14	Zn/Ni	Alumzite	17.8/0.7	29.22/1.15	12.08/0.48
15 Control	Zn/Co	none	5.1/0.2	15.69/0.62	8.45/0.33
16	Zn/Co	Xylan	17.8/0.7	39.94/1.57	12.93/0.51
17	Zn/Co	E6108	30.5/1.2	22.20/0.87	8.48/0.33
18	Zn/Co	E9000	17.8/0.7	69.55/2.74	23.21/0.91
19	Zn/Co	M3400A	17.8/0.7	30.76/1.21	14.43/0.57
20	Zn/Co	Saci 445A	17.8/0.7	61.07/2.40	35.98/1.42
21	Zn/Co	Alumzite	17.8/0.7	29.75/1.17	7.84/0.31

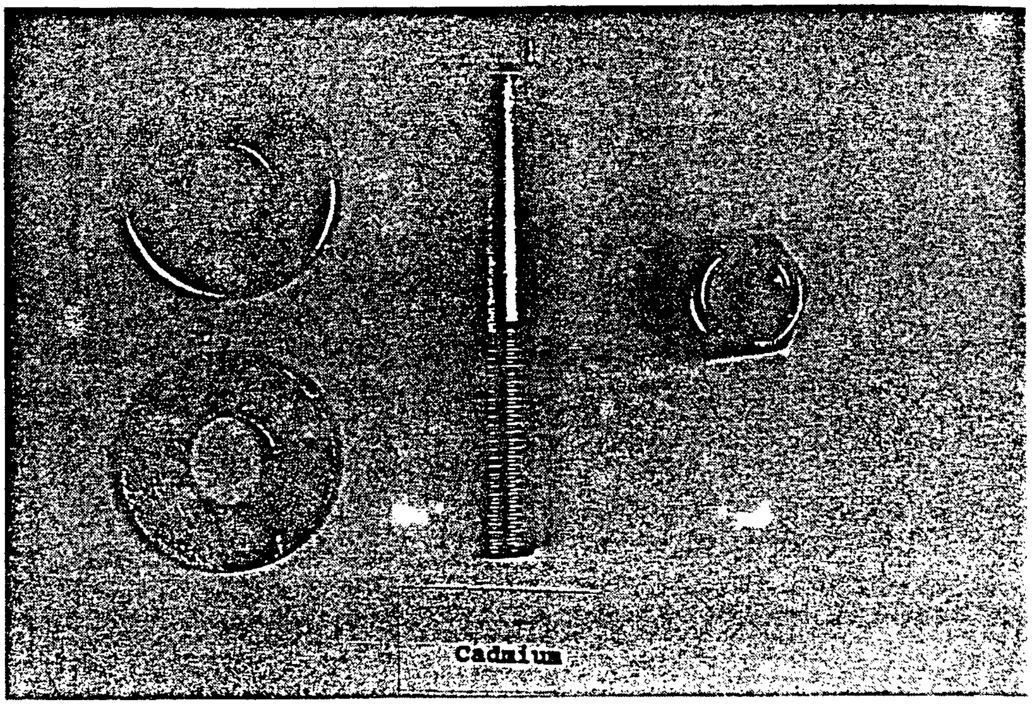
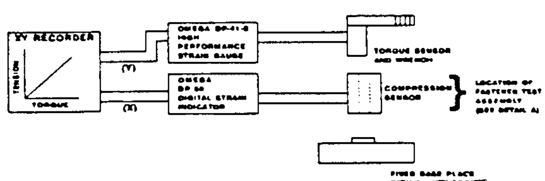


Figure 1 Representative Test Fastener Set (1/2-20 UNC Fine, Grade 5) Coated with QQ-P-416E, Class 3, Type II Cadmium Plating.

APPARATUS



DETAIL A

FASTENER TEST ASSEMBLY

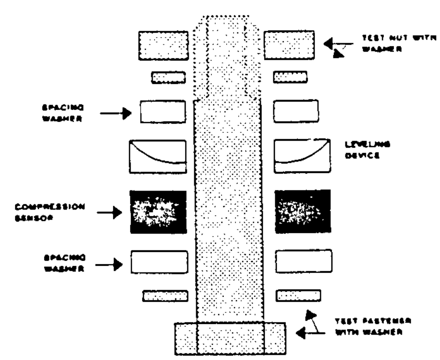


Figure 2 Torque-Tension Measurement Apparatus.

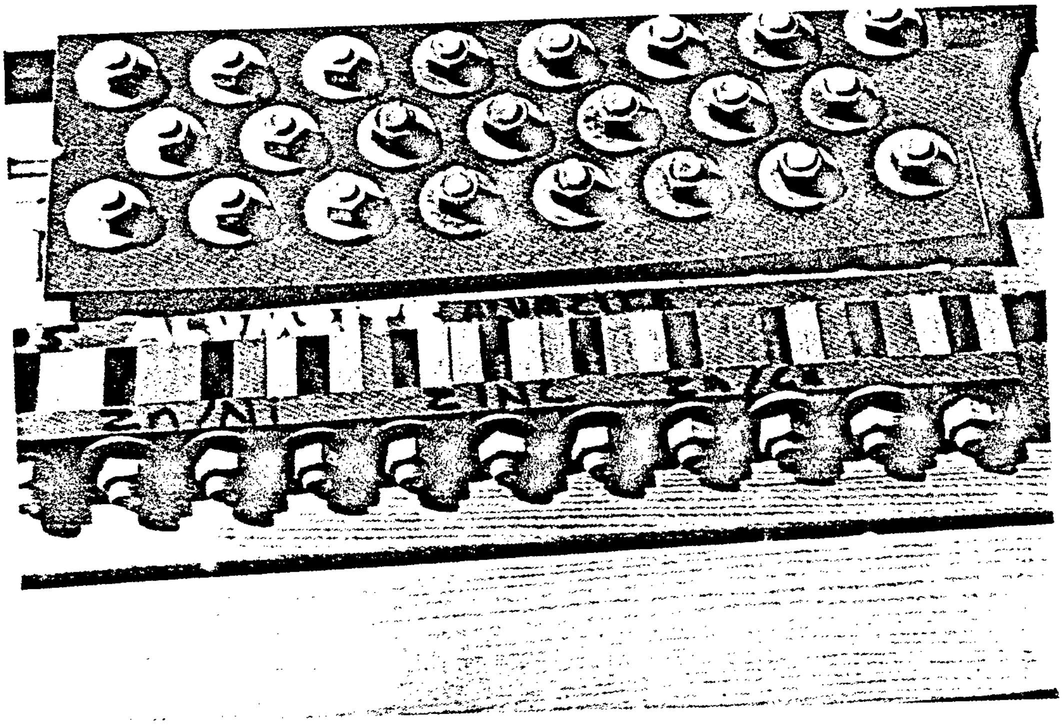


Figure 3 Marine Atmosphere Exposure Test Racks Showing Alternative Specimen Orientations.

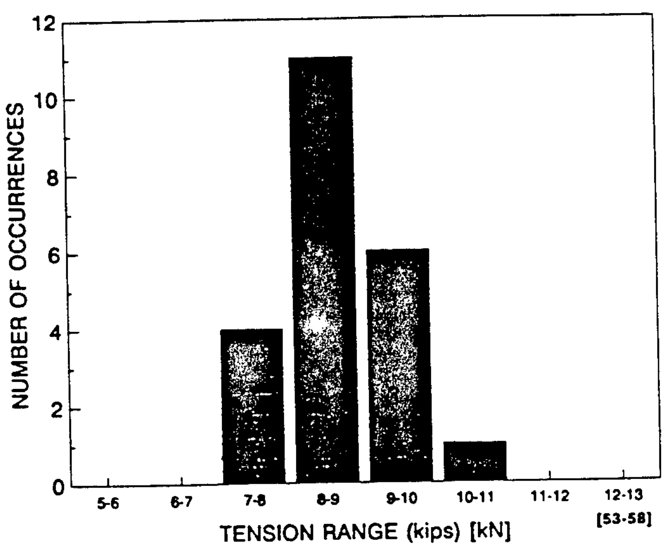


Figure 4 Tension Distribution Histogram Based on Twenty Replicate Cadmium Coated Fasteners at an Applied Torque of 80 ft * lbs [108 N * m].

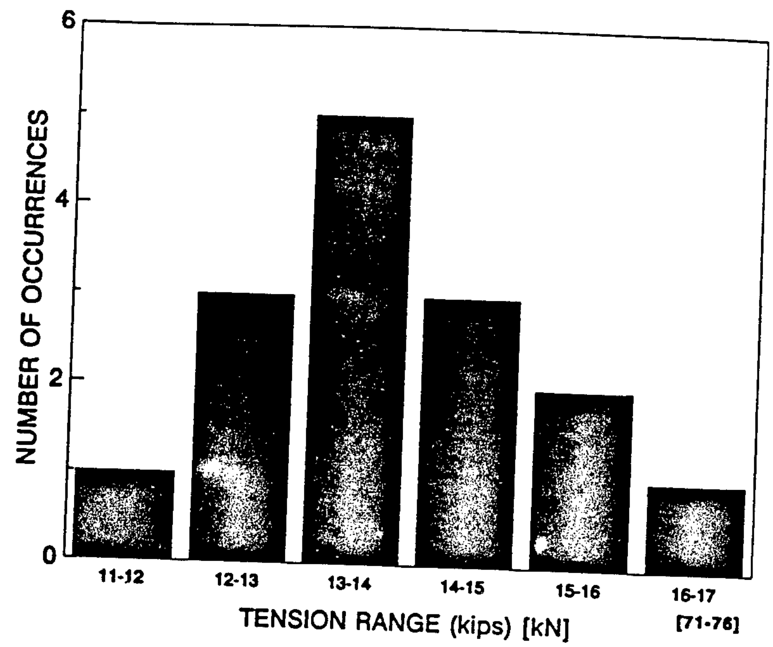


Figure 5 Tension Distribution Histogram Based on Fifteen Replicate Zinc-Molykote 3400A Coated Fasteners at an Applied Torque of 100 ft * lbs [135 N * m].

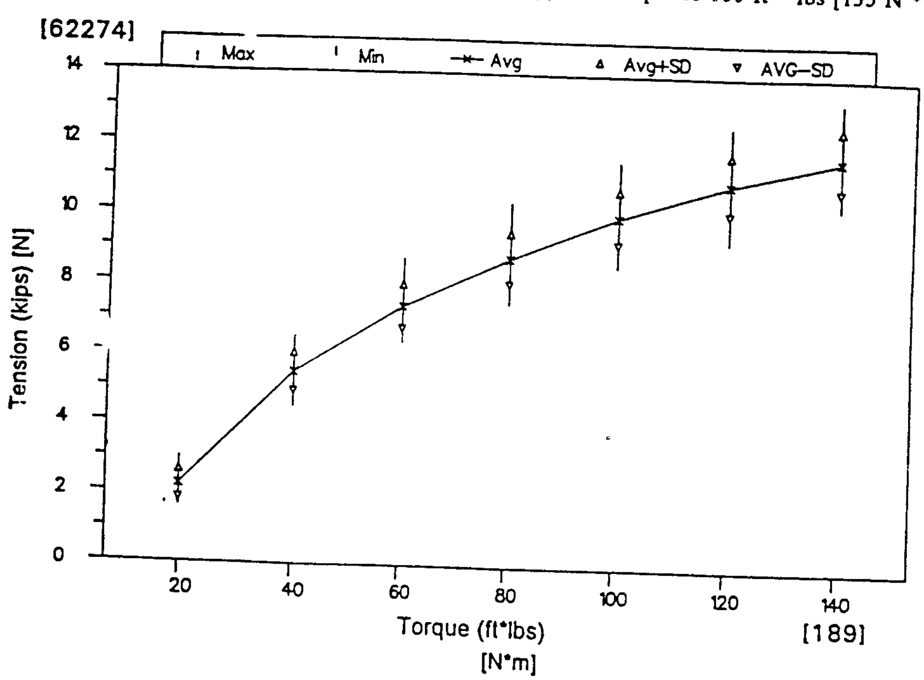


Figure 6 Torque-Tension Data From Twenty Replicate Cadmium Coated 1/2-20 UNC Fine, Grade 5 Fasteners.

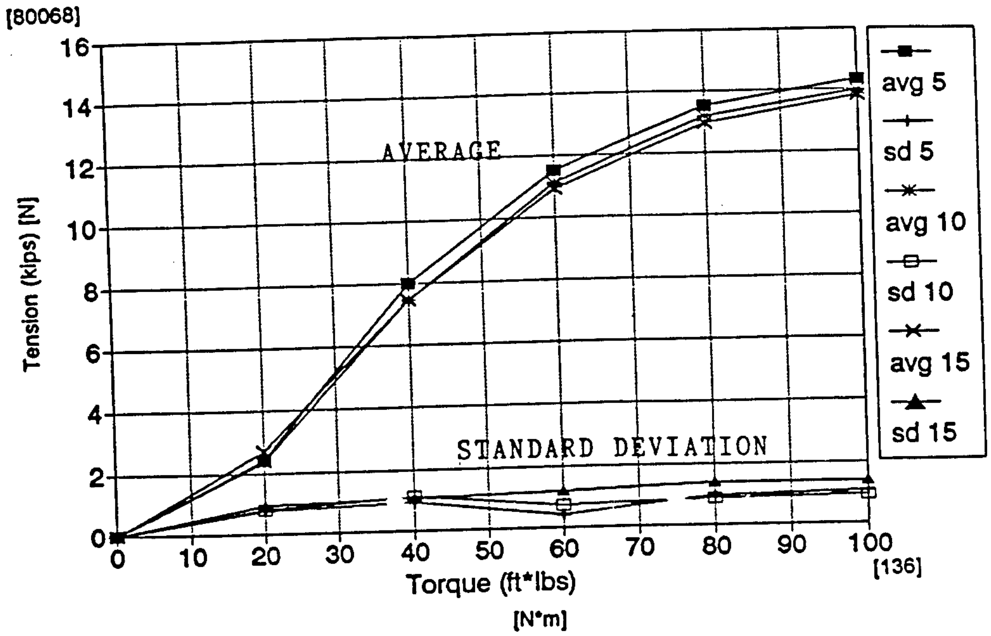


Figure 7 Torque-Tension Plots for Five, Ten, and Fifteen Duplicate Zinc-Molykote 3400A Coated Fasteners.

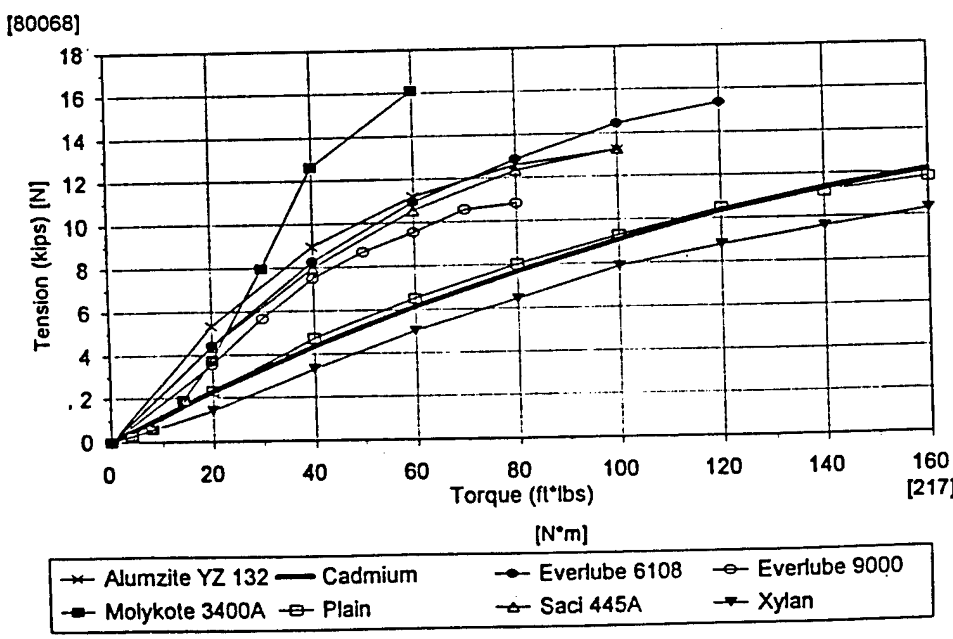


Figure 8 Torque-Tension Data From Five Replicate Fasteners Coated with Zinc and the Alternative Lubricous Topcoats.

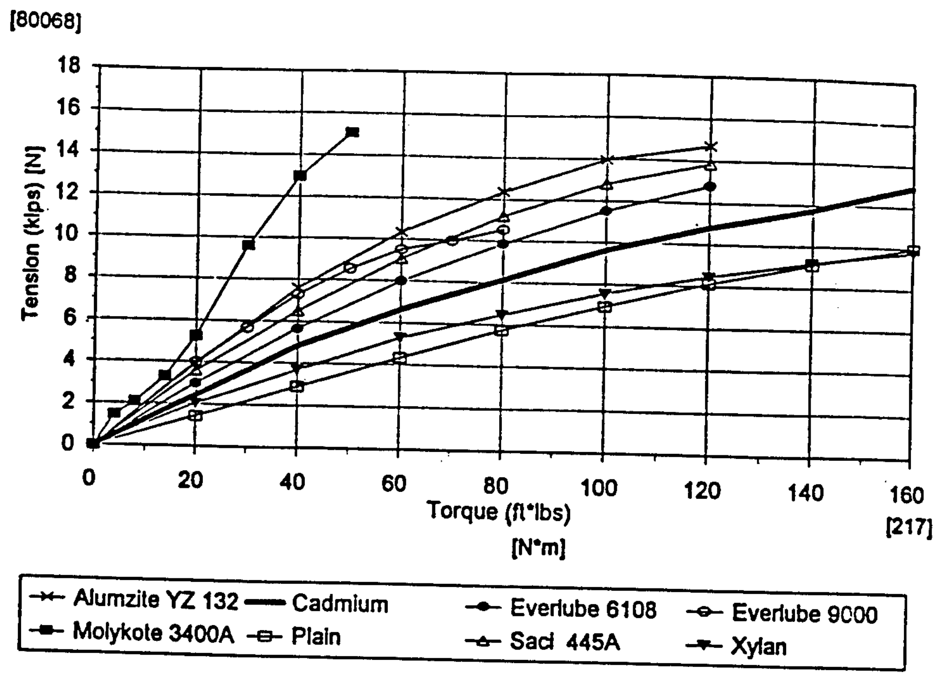


Figure 9 Torque-Tension Data From Five Replicate Fasteners Coated with Zn/Ni and the Alternative Lubricous Topcoats.

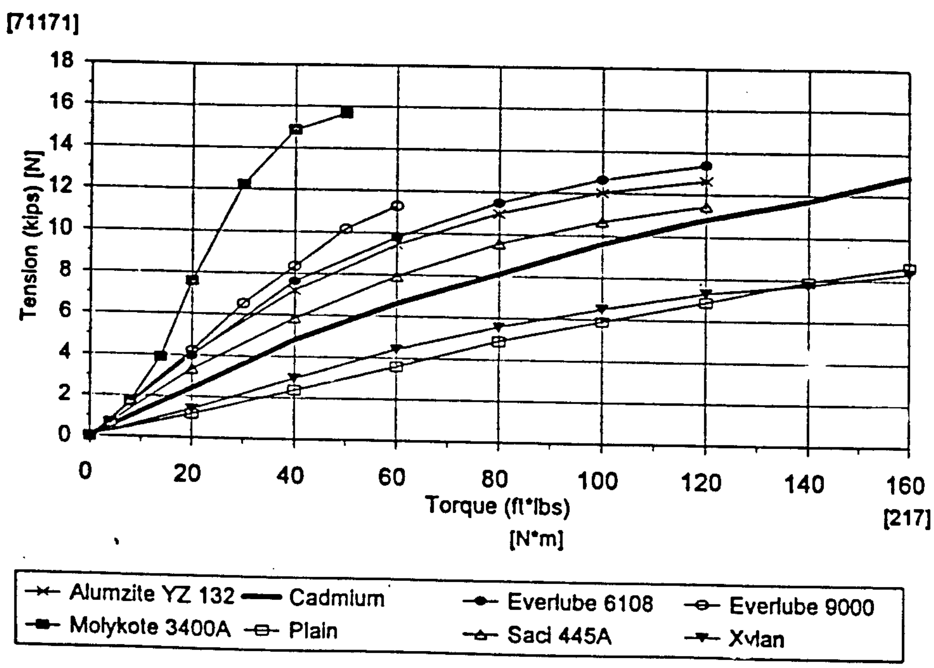


Figure 10 Torque-Tension Data From Five Replicate Fasteners Coated with Zn/Co and the Alternative Lubricous Topcoats.

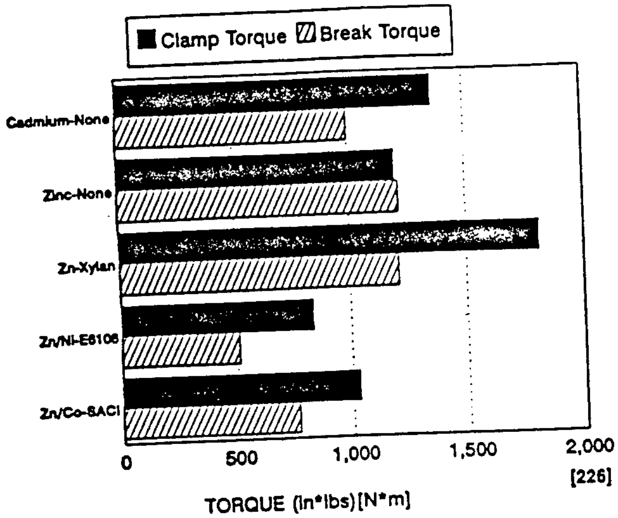


Figure 11 Average Applied Torque Required to Tension Fasteners to 10,000 kips [44,482] and to Break Tensioned Fasteners Loose After 2500-hours of Marine Atmosphere Exposure.

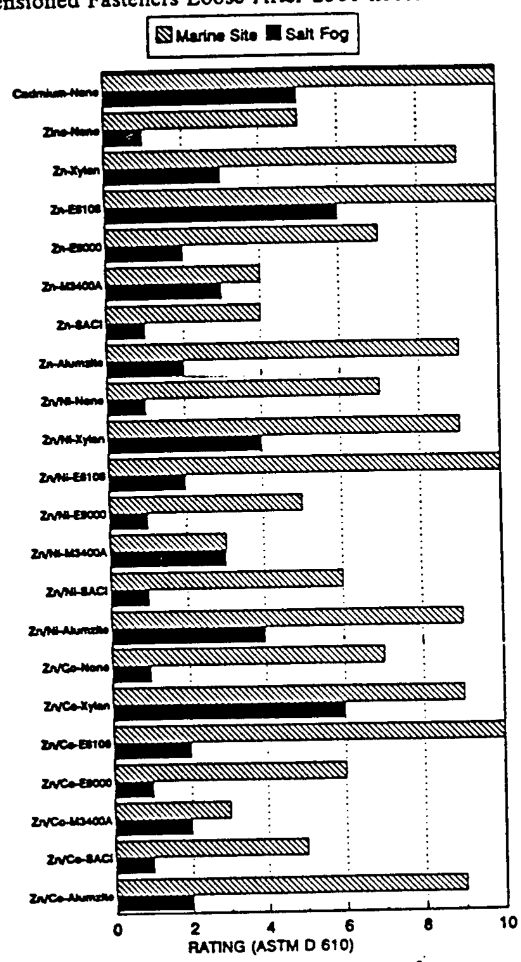


Figure 12 Average Coating System Corrosion Control Performance as Measured by 2500-hour Marine Atmosphere Exposure Testing and 1000-hour of ASTM B 117 Salt Fog Testing.